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Effects of electrokinetic phenomena on the load-bearing capacity of different steel and concrete piles: A small-scale experimental study

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ABSTRACT

To date, the electrokinetic (EK) method has only been used to increase the bearing capacity of steel piles. This study analysed the impact of EK on the bearing capacity of reinforced cement concrete piles (RCCP), reinforced lime-cement concrete piles (RLCCP), and steel piles (SP) located in kaolin clay. The performance of four different cathodes was also evaluated, and the iron electrode was found to be the most effective cathode for using in EK process. Unlike RLCCP, the bearing capacity of 7-day cured RCCP with 5-day EK decreased due to corrosion in the pile body. However, the addition of lime to RCCP significantly increased the pile bearing capacity by 57.8% with 8-day EK and prevented damage and corrosion in the pile body. It is concluded that EK can effectively increase the bearing capacity of both metallic and even concrete piles.

Keywords: Kaolin clay; Concrete pile; Electrokinetic; Bearing capacity.

Introduction

Piles are used as deep foundations to support heavy structures built on soft soils due to their potential for large settlement and low strength. Electrokinetic (EK), as an environmentally friendly and cost-effective soil treatment technique, can be used to alleviate soft soil problems. EK improves soil permeability through electro-osmosis, electrophoresis, and change in soil chemical properties (Malekzadeh 2016). The use of EK has been reported as an effective method for soil consolidation in laboratory scale and in the field (Lamont-Black et al. 2012), which increases the bearing capacity of piles (El Nagger and Routlendge 2004).

Electrode materials have considerable effects on the performance of electro-osmotic phenomenon. Electrodes are made of either metallic or non-metallic conductor interfaces (Mohamedehassan and Shang 2001). A new type of electrode called geosynthetic electrodes made of conductive polymers are also suitable for soil consolidation due to their high resistance to chemicals in the soil (Estabragh et al. 2014).

Up to now, EK method has only been used to increase the bearing capacity of steel piles. In the first part of the current study, the most effective cathode among stainless steel, iron, copper, and aluminium was determined based on their effects on consolidation. Then, the effect of EK treatment on the bearing capacity of different steel and concrete piles was investigated.

Materials and methods

A kaolinite clay soil was used for consolidation tests in a glass box with the dimensions of 200×200×150mm. All vertically located electrodes and drainage valves were installed at a distance of 140mm from the bottom of the box. A filter layer was used to prevent soil penetration into electrodes (Estabragh et al. 2014). Chemical and physical properties of the used raw materials and their mix proportions to prepare the concrete piles are provided in Jahandari et al. (2019).

Water was added to the air-dried clay at a rate 5% more than the liquid limit of the clay soil in the above-mentioned glass box. Soil was kept in a closed container for 24hr to achieve a uniform water distribution. The preloading phase was completed with the application of 27kPa load when the soil settlement was stopped after eight days. Then, 25 constant voltage potential was applied to electrodes for 840 minutes. After conducting EK, the vane shear strength and moisture content of clay soil in the vicinity of electrodes were measured for iron-iron, iron-copper, iron-aluminium, and iron-stainless steel electrodes.

In the second phase, a 180×180×300mm glass box was used for the tests. Iron electrodes with 300mm length and 20mm diameter were mounted at *2D* (*D* is pile diameter) distance from the pile body with a square arrangement (Vocciante et al. 2016).

All tested piles were 180mm in length and 20mm in diameter. An iron reinforcing bar with 6mm diameter was located inside concrete piles to provide conductivity.

Results and analysis

Performance of electrode type

Water drained

Fig. 1(a) shows the variations in the volume of drained water versus time when the EK treatment was finished. At the beginning of the process, more water was drained from cathodes. Over time, soil and electrode resistance increased, and electrodes became corroded. Therefore, the intensity of electric field created in the soil decreased, which in turn decreased the electro-osmotic performance. The highest and lowest rate of water drainage was observed for iron and aluminium cathodes, respectively.

Water content

The initial soil moisture content before the EK process was 33.2%. The changes in the soil moisture content based on the distance from anode are shown in Fig.1(b). The greatest decrease in the water content at the adjacent anode was observed for iron-iron electrodes.

Vane shear strength

The decomposition of water molecules during the EK process leads to the formation of H^+ ion (acidic agent) in the anode adjacent and OH^- ion (alkaline agent) in the cathode.

Chemical equilibrium equations in the electrolysis process that break down water molecules are as following (Estabragh et al. 2014):

$$2H_2O - 4e = 4H^+ + O_2 \quad (1)$$

$$2H_2O + 2e = 2OH^- + H_2 \quad (2)$$

The acidity of soil and the deposition of ions around electrodes cause formation of cementation and increase soil shear strength during EK (Estabragh et al. 2014). Fig.1(c) shows soil vane shear strength in the adjacent anodes, cathode, and between electrodes. The maximum and minimum shear strengths were observed for the clay soil around copper and aluminium cathodes, respectively.

Power consumption

The power consumption (E) by electrodes was calculated using Eq.3 (Malekzadeh 2016):

$$E=1/v_s\int^t UI\,dt \quad (3)$$

where v_s is soil volume, U is applied voltage, and I is electric flow. Using Eq.3, iron and aluminium cathodes had the highest and lowest power consumption (102.6, 63.0 kWh/m) and water drainage (20.1%, 14.0%), respectively. The variation history of the current is also shown in Fig. 1(d).

Bearing capacity

EK with 25V was applied to a series of piles and electrodes for 1, 3, 5, and 8 days (Fig.2(a, b)). To measure the pile's bearing capacity, static load was applied according to ASTM D-1143 (2013) (Fig.2c). Corrosion was observed in RCCP body and a part at the bottom of pile was detached after the pile was removed from the soil (Fig.2d). The reasons for corrosion in pile and reduction in the pile bearing capacity can be explained as:

1. The RCCP adjacent to anode was not resistant to acidic environment created during EK.
2. By installing electrodes in electrolyte system, negative charged particles moved to the positive electrode and were absorbed by the anode. The absorption and diffusion of ions and sulphates in anode can cause corrosion in pile.
3. The curing time of RCCP was influenced by the permeability of ions, and 7-day curing period was not enough to make RCCP impermeable against ions and sulphates.

To solve the problem associated with RCCP including corrosion and low bearing capacity, the curing time was increased to 28 days and 50% of the Portland cement used in

RCCP was replaced by hydrated lime. Thus, to investigate the effects of curing time on the corrosion resistance of RCCP while performing EK, two RCCPs cured for 28 days were subjected to 25V for 5 and 8 days, and then static loading was applied. Also, to find out the effect of lime addition to RCCP and to compare the results with SP, four SPs and RLCCPs cured for 7 days were subjected to EK for 1, 3, 5, and 8 days, and then the static loading was applied on the piles.

Pile bearing capacity was calculated using the load-settlement curves (Fig.3). For each pile type, four piles without EK were loaded as control samples. As shown in Fig.3 (a), the bearing capacities of 7-day cured RCCP and SP with 1-day EK increased by 22.6% and 22.3% compared to the control sample, respectively. The bearing capacities of 7-day cured RCCP and SP with 3-day EK were 36.5% and 29.3% higher than those without EK, respectively. The increases in the bearing capacities of RCCP with and without EK in 3-day were 38.1% and 1.0% compared to the first day of pile installation, respectively. As illustrated in Fig. 3c, the bearing capacity of RCCP cured for 7 days and subjected to EK for 5 days decreased significantly.

According to Fig.3 (e, f), the bearing capacity of 28-day cured RLCCP with 5-day EK was similar to 7-day cured RCCP with 3-day EK. The RLCCP bearing capacity increased by 29.8% after using EK for 5 days compared to the control pile. Increasing the curing time decreased the power flow, resulting in a lower rate of increase in the bearing capacity over time. RLCCP's bearing capacities with 5 and 8 days EK increased by 30.9% and 40.8% compared to similar piles without EK, respectively. Damage or corrosion in RLCCP with 8-day EK was not occurred since lime is alkali and has more resistance to acidic environment.

Theoretical bearing capacity

The bearing capacity of piles (Qu) was calculated using Eq.4 (Das 2008).

$$Qu = Qs + Qp = (\alpha\ Cu\ As) + (9\ Cu\ Ap) \quad (4)$$

where Qs is the frictional resistance of the pile body, α is empirical adherence factor, Cu is soil shear strength, As is the pile lateral surface area, Qp is the tip resistance of the pile, and Ap is the pile cross sectional area.

After loading, the frictional resistance of the pile body and the pile tip were measured, and the theoretical bearing capacities of the piles were calculated using Eq.4 and were compared with experimental results (Fig.4). The results show that the theoretical bearing capacities of all piles were slightly higher than those measured experimentally. Perhaps, the reason is that although EK effectively consolidated the soil in a short time, the compaction rate of the soil did not reach to nearly the maximum rate in real ground condition.

Conclusions

According to the findings and discussions presented in this study, the following main conclusions can be drawn:

- Iron and aluminium exhibit the highest and the lowest volume of water drained from the soil.
- The use of EK increases SP's bearing capacity by 98% after 8 days compared to the control model.

- The bearing capacity of 7-day cured RCCP under 3-day EK increases. However, after using EK for 5 days, a significant decrease in the bearing capacity of pile will be observed due to the occurrence of corrosion in the pile body.
- Either increasing the curing time or adding lime to RCCP materials, increase the corrosion resistance of pile significantly.
- EK can significantly increase the bearing capacity of metallic and even concrete piles.
- Theoretical bearing capacities of all piles are slightly higher than those measured experimentally since although EK effectively consolidates soil in the short time, the compaction rate of soil does not reach to nearly the maximum rate in real ground condition.

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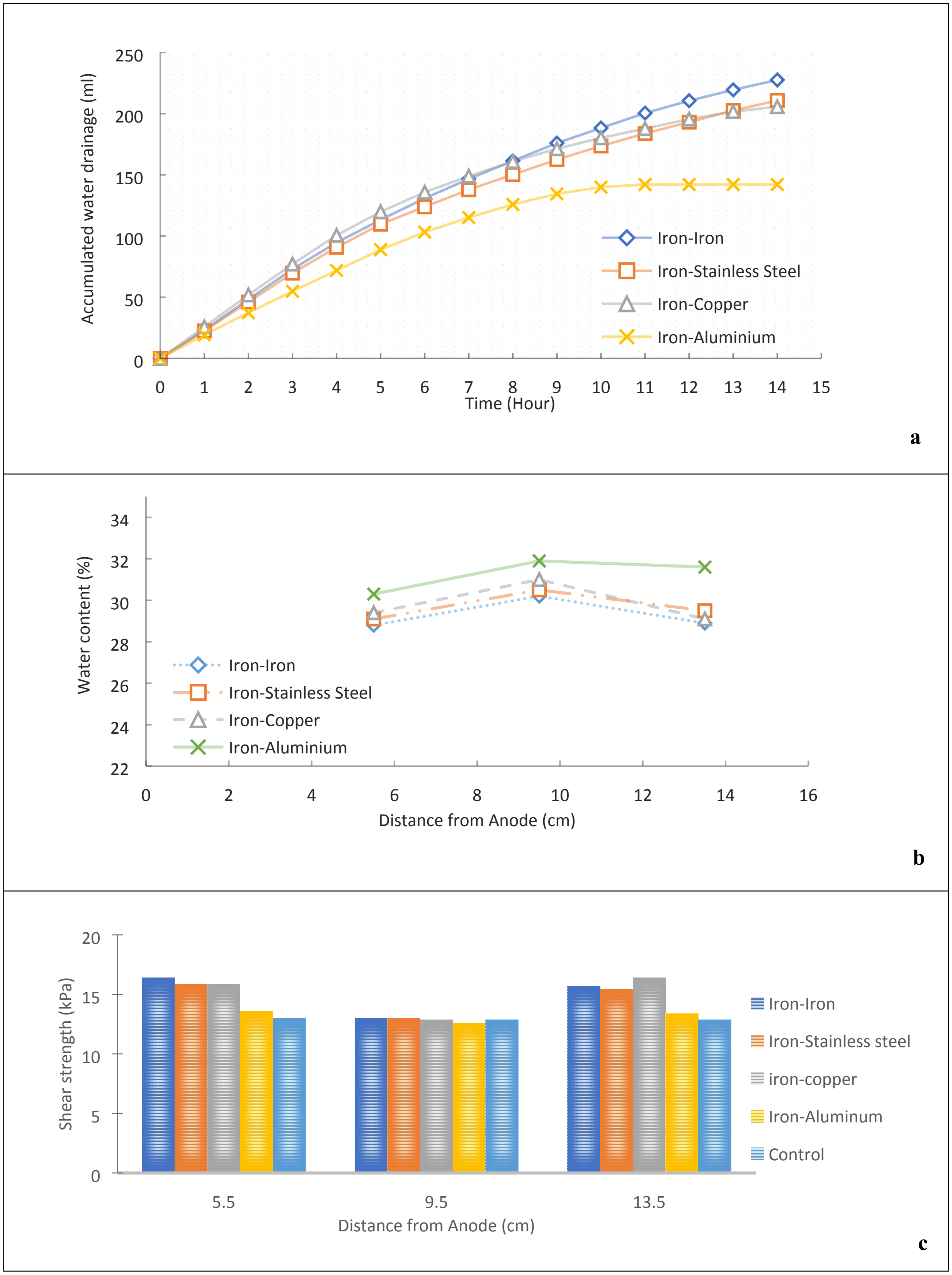
Accumulated water drainage (ml)
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Time (Hour)
Iron-Iron
Iron-Stainless Steel
Iron-Copper
Iron-Aluminium
a
Water content (%)
34
32
30
28
26
24
22
0 2 4 6 8 10 12 14 16
Distance from Anode (cm)
Iron-Iron
Iron-Stainless Steel
Iron-Copper
Iron-Aluminium
b
Shear strength (kPa)
20
15
10
5
0
5.5
9.5
13.5
Distance from Anode (cm)
Iron-Iron
Iron-Stainless steel
iron-copper
Iron-Aluminum
Control
c

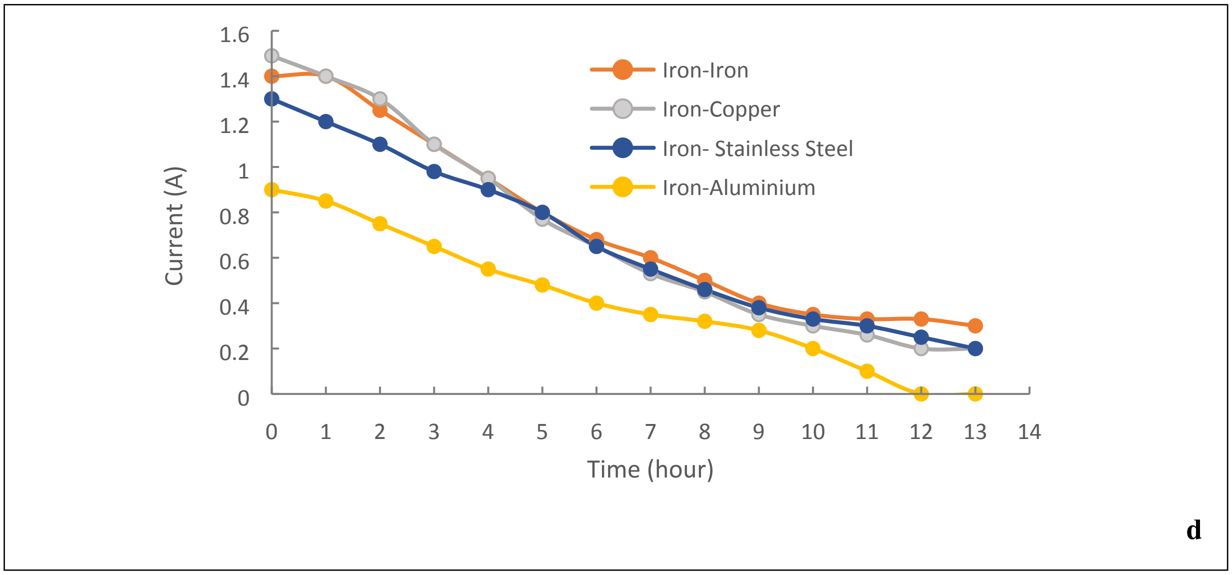

Figure 1. (a) accumulated water drainage for different cathodes under EK, (b) water content based on distance from the anode for four electrode types, (c) undrained vane shear strength after EK process for all electrode pairs, (d) current versus time for four electrode types.

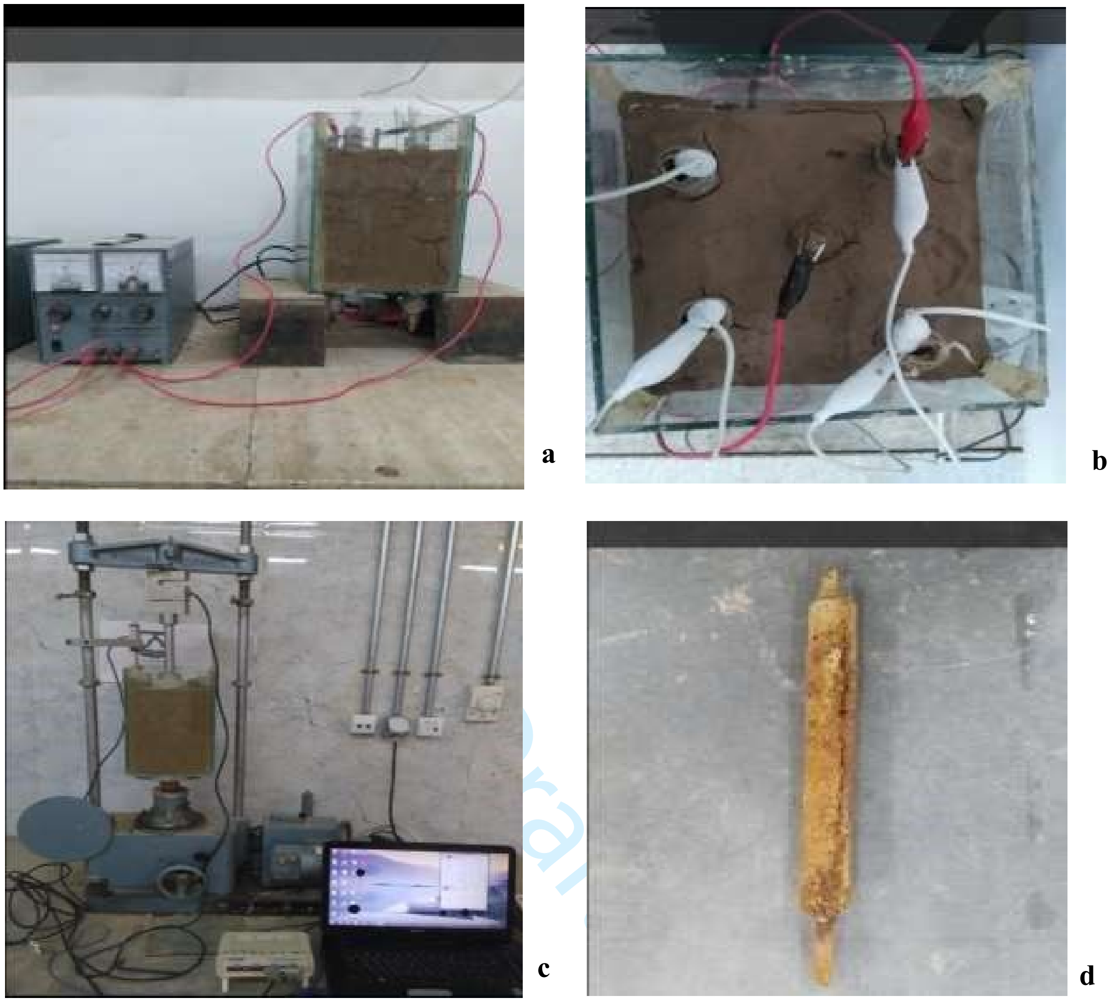

Figure 2. The RCCP under EK: (a) front view; (b) top view, (c) Static loading on pile, (d) 7-day concrete pile with 5-day EK after removal from soil.

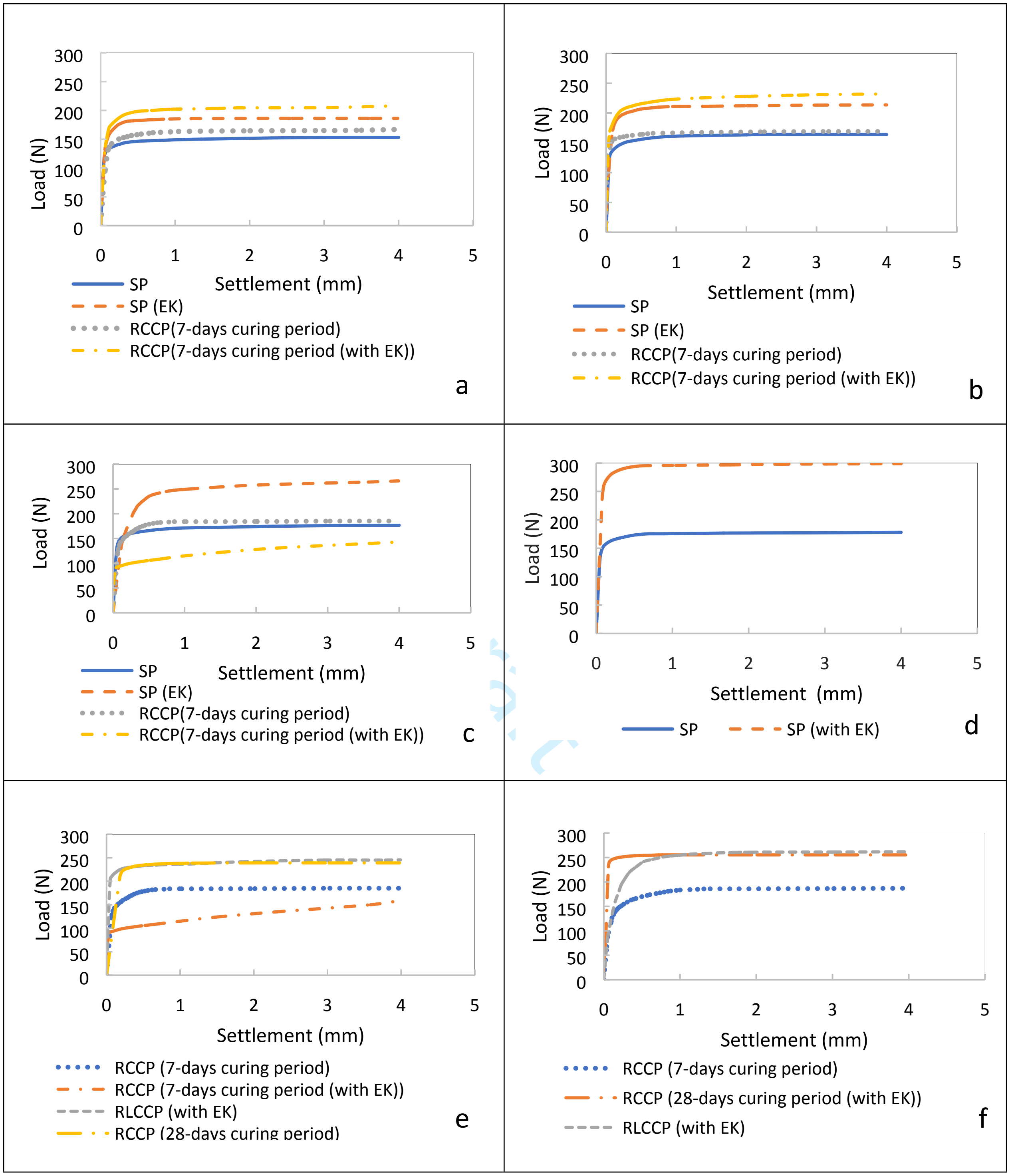

Figure 3. Load versus settlement curve with and without EK under static load for (a) 7-day cured SP and RCCP with 1-day EK, (b) 7-day cured SP and RCCP with 3-day EK, (c) 7-day cured SP and RCCP with 5-day EK, (d) 7-day cured SP with 8-day EK, (e) 28-day cured RCCP and 5-day cured RLCCP, (f) 28-day cured RCCP and 8-day cured RLCCP

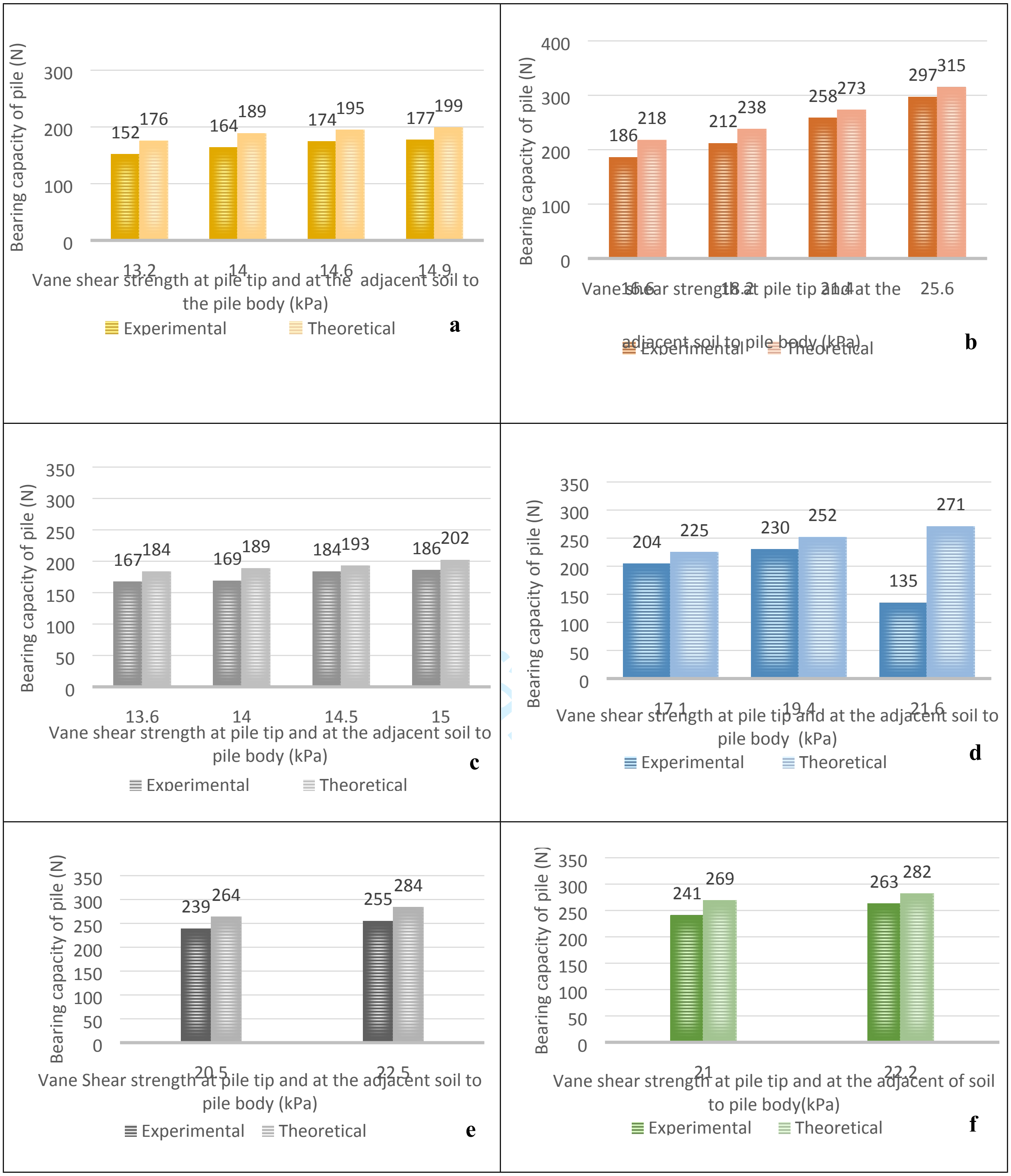

Figure 4. Comparison between the experimental and theoretical vane shear strength at the pile tip and at the adjacent soil to pile body (a) SP without EK, (b) SP with EK, (c) RCCP with 7-day curing without EK, (d) RCCP with 7-day curing with EK, (e) RCCP with 28-day curing with EK, (f) RLCCP with EK.